

VARYING HYDROLOGIC ANALYSES TO MATCH LEVEL OF AVAILABLE  
INFORMATION IN ETHIOPIA

A Thesis

Presented to the Faculty of the Graduate School  
of Cornell University

In Partial Fulfillment of the Requirements for the Degree of  
Master of Science

by

Benjamin Mark Liu

January 2008

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## ABSTRACT

Two separate papers are presented as a way to illustrate how hydrologic analyses should be tailored to fit the amount of information available for a watershed and the intended audience.

The first paper highlights two watersheds in the highlands of Ethiopia where participatory water resource management activities were used to overcome a shortage of scientific information. These watersheds brought together many different implementing agencies to address water scarcity, crop production, and soil erosion, but the most important step was enabling local potential through the creation and strengthening of community watershed management organizations. Leadership training and the reinforcement of stakeholder feedback as a fundamental activity led to increased ownership and willingness to take on new responsibilities. A series of small successes ranging from micro-enterprise groups to gully rehabilitation have resulted in the pilot communities becoming confident of their own capabilities and proud to teach others how to manage a watershed.

The second paper describes a simple method of characterizing three other watersheds in the Ethiopia highlands where basic hydrologic data was already available. Effective precipitation and runoff were summed for various timescales, with weekly hydrographs and biweekly comparison plots proving the most descriptive. The latter graphs showed that discharge was linearly dependent on effective precipitation after a certain amount of rainfall had fallen in each watershed. The hydrographs also confirmed the importance of storage in catchment response behaviors, suggesting that the historical tendency to focus conservation efforts on preventing infiltration excess runoff may not

be appropriate for reducing overall water loss. Simple analyses like these should be used to gain an understanding of mechanisms before attempting more complicated modeling techniques.

## BIOGRAPHICAL SKETCH

Benjamin Liu was born in Longmont, Colorado on December 22, 1978. His parents, Jackie Porter and Mark Liu, and brother, Michael, still live in Colorado and wonder if he'll ever return.

Benjamin earned a B.S. in Engineering (Civil Specialty) from the Colorado School of Mines in 2001. After graduating, two years spent working as a Water & Sanitation Volunteer in Jamaica convinced him to return to school to pursue a graduate degree in water resources at Cornell University.

## ACKNOWLEDGMENTS

Yitayew Ababe, Tesfaye Habtamu, and Kent Reid of the AMAREW project were responsible for successfully promoting participatory watershed management in the Yeku and Lenche Dima watersheds (Chapter 2). Personnel at BoARD, ARARI, and other partner agencies were also instrumental in facilitating the project. USAID provided funding to Virginia Tech (Contract No. 663-C-00-02-00340-00) which subcontracted the watershed component to Cornell University. Yitayew Abebe, Oloro McHugh, Amy Collick, Brhane Gebrekidan, and Tammo Steenhuis all contributed to the Chapter 2 paper.

Enyew Adago and Gete Zeleke of ARARI, and Hans Hurni and Ato Terese of the SCRP were each instrumental in gaining access to the raw data used in Chapter 3. Tewodros Assefa and Sisay Demeke of ARARI along with the dedicated research assistants at each watershed deserve special recognition for kindly helping me to observe the sites firsthand. I was able to conduct research in Ethiopia thanks to a travel grant from the Mario Einaudi Center for International Studies.

Most importantly, I would like to warmly thank my parents and my committee members, Tammo Steenhuis, Todd Walter, and Steve DeGloria, for their patient guidance and cheerful support during my years at Cornell.

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## CHAPTER 1

### Introduction

This thesis consists of two separate papers, chapters 2 and 3. Each chapter describes a different method of characterizing Ethiopian watersheds. The modern natural resources manager has a bewildering number of analysis tools available to them, but most tools are only effective under the proper circumstances. Realizing when each watershed analysis tool is appropriate can be far more valuable than just acquiring knowledge of these techniques. Both the level of information available and the capacity for disseminating results should be considered when planning a development project. To help learn how to match different circumstances with the appropriate analysis, this thesis examines two different situations that often occur in remote locations: a watershed with scarce or no research infrastructure, and a watershed with basic hydrologic measurements but little analysis.

Chapter 2 presents the natural resources development that is being carried out in the Yeku and Lenche Dima watersheds of northern Ethiopia. When the Amhara Micro-enterprise development, Agricultural Research, Extension, and Watershed Management (AMAREW) Project started there was very little information available to project planners, so a participatory approach was chosen to address the land degradation issues of each site. This method relied heavily on training the local communities in leadership and using a succession of small projects to build confidence and skills in watershed protection. A lack of scientific information was offset by local knowledge, with this focus on community objectives bringing the added benefit that positive results were readily understood by all of the diverse stakeholders.

Chapter 3 presents a rainfall-discharge analysis that was performed for the Andit Tid, Anjeni, and Maybar watersheds, also of northern Ethiopia. The Soil Conservation Research Programme (SCRIP) established modest monitoring stations in each of these sites during the 1980's, with climate and stream flow measurements being recorded up to the present. With the formal project ended, control of the study sites has been given to local research institutions. The downside of this transfer is that natural resources managers, sometimes not previously involved with the studies, have suddenly found themselves responsible for a daunting amount of data collection and analysis. Methods to present this scientific information in a relatively simple manner are needed so that people besides specialized hydrologists can see the importance of continued data collection. With this in mind, using easily understood spreadsheet calculations, rainfall-discharge relationships were developed to explore this moderate level of data and provide insight into catchment-level runoff mechanisms.

## CHAPTER 2

### Overcoming Limited Information through Participatory Watershed Management:

#### Case study in Amhara, Ethiopia

#### **Introduction**

Ethiopia's population grows by 2 million per year. In a country dependent on subsistence farming, this increasing pressure has resulted in average land holdings falling from 0.5 ha/person in 1960 to 0.11 ha/person in 1999 (Special Report: FAO/WFP Crop and Food Supply Assessment Mission to Ethiopia 2006). The Ethiopian government has officially recognized that 5-6 million of its people have lost the capacity to procure enough food to meet annual needs under normal conditions, with another 10 million susceptible to any shock, so projects that protect and improve the natural resource base are necessary for long-term survival. Since both arable land and surface water sources are severely limited, improving the soil's capacity to store rainwater was investigated. Over 90% of Ethiopia's food production comes from rain-fed agriculture so improvements in the management of this 'green' water have enormous significance.

Ongoing land degradation in Ethiopia requires urgent action at different levels of society (Nyssen et al. 2004). Nyssen et al. (2004) indicated that the stagnation of agricultural technology and lack of agricultural intensification in the Ethiopian highlands is the origin of present land and resource degradation. This degradation in turn becomes the underlying root of poverty. Thus, the challenge of breaking the poverty-environment trap and initiating sustainable intensification requires policy incentives and technologies that confer short-term benefits to the poor while conserving the resource base. Only by improving the natural resource base can one increase food

production and lessen the need for external food supplies (Shiferaw and Holden 1998).

Therefore, to explore sustainable methods towards increased food production and its connected economic development, the goal of this study was to revitalize watersheds by keeping more rainwater ('green' water) on the land and increasing fertility. This revitalization is multidimensional and complex, requiring interdisciplinary effort to carefully design development activities. Since 'green' water development encompasses so many different activities at various scales, with each location having unique needs, an integrated approach is especially appropriate.

#### *Integrated watershed approaches*

One integrated approach for watershed management is through the use of computer models – various attempts have been made in Ethiopia to apply such methods. The Agricultural Non-Point Source Model (AGNPS) was tested on the highlands Augucho catchment by Haregeweyn and Yohannes (2003) but could not reproduce runoff patterns. The Precipitation-Runoff Modeling System (PRMS) was similarly tested by Legesse et al. (2003) for South Central Ethiopia, and needed extensive calibration to predict the monthly runoff. Ayenew and Gebreegziabher (2006) fitted a spreadsheet type water balance to predict water levels in Lake Awassa of the Rift Valley, but found that the model did not perform well in more recent years, possibly due to changing land use and neotectonism. Finally, Hengsdijk et al. (2005) applied a suite of crop growth, nutrient balance, and water erosion models to conclude that common conservation practices such as bunds, crop mulching, and reforestation may actually result in lower overall crop productivity in the highlands of northern Ethiopia.

In response to Hengsdijk's conclusions, Nyssen et al. (2006) compared Hengsdijk's predictions with field observations from the same region and found that the models

over predicted crop yields while under predicting soil losses. Although such models can be applied for policy analysis, they typically need extensive calibration and cannot simulate the intricacies that farmers have to deal with on a day by day basis (Nyssen et al. 2006). When datasets are incomplete or of poor quality, other integrated approaches will likely be more effective management tools.

The modeling techniques described above were typically developed for conditions in the United States or Europe where availability of datasets for both input and calibration was not a great limitation. In contrast, the required datasets in developing countries are often available only at very limited locations, and data collection standards can be inconsistent. Integrated water management approaches that either require less information or make use of indigenous knowledge within the watershed are therefore needed. One such approach is the Smallholder System Innovations (SSI) programme in Tanzania and South Africa, which concentrates on ways to increase food production, improve rural livelihoods, and safeguard critical ecological functions through participatory development and interdisciplinary research (Rockstrom et al. 2004). Similarly, using the joint Vertisols project in Ethiopia as a case study, Jabbar et al. (2001) described the need to transition away from the traditional single discipline manner of research if complex interrelationships between environment and human are to be addressed.

Another reality of development work in Ethiopia is a dependency on food aid. It has become a contentious issue for many developing countries, with some officials even advocating the cessation of foreign aid. After more than 25 years of Food for Work programs, productivity of major crops (barley and wheat) remained stagnant, and local livelihoods in Ethiopia were not improved (Herweg 1993, Shiferaw and Holden 1998,

and Tekle 1999). Conservation practices proposed under the Food for Work program were not seen by households as valuable means towards increasing food production. Farmers took part in the Food for Work programs because either they needed the grain or were forced to participate (Tekle 1999). Tekle further showed in a study of South Wollo, Ethiopia that the main problem with Food for Work programs was the lack of attention given to attitudes of local people towards conservation programs and what their priorities were. In most programs local people were not consulted at all, making it impossible for these communities to accept any kind of responsibility. Public opposition to projects most often arises from either a lack of accurate knowledge or inadequate involvement in the decision-making process (Planning and Decision Making 1999), so the obvious solution is to have farmers become involved in both the information gathering and decision processes. Therefore, our integrated watershed management approach was to give local farming communities control of both the planning and distribution of Food for Work aid, thus meeting short-term food needs while sustainably improving the resource base.

### *Pilot Watersheds*

With this in mind, two pilot watersheds from food insecure areas of the Amhara region, Yeku and Lenche Dima, were selected in conjunction with the Amhara Micro-enterprise development, Agricultural Research, Extension, and Watershed Management Project (AMAREW) to test integrated watershed management techniques in Ethiopia. Locations of these sites are shown in Figure 2.1. Both watersheds are almost entirely comprised of subsistence farming. Rain-fed crops, mostly cereals, are cultivated in the flatter valley bottoms while the hillsides are used for free livestock grazing. Yeku watershed is more at risk of chronic food shortage than Lenche Dima and was recently involved in the government's resettlement scheme. As shown in Table 2.1, Yeku is

higher in altitude, receives less rain, and is economically poorer as illustrated by smaller average landholdings. While the only developments within each watershed are small traditional villages and paths, Lenche Dima is near the larger town of Woldiya so has easier access to outside resources and markets.

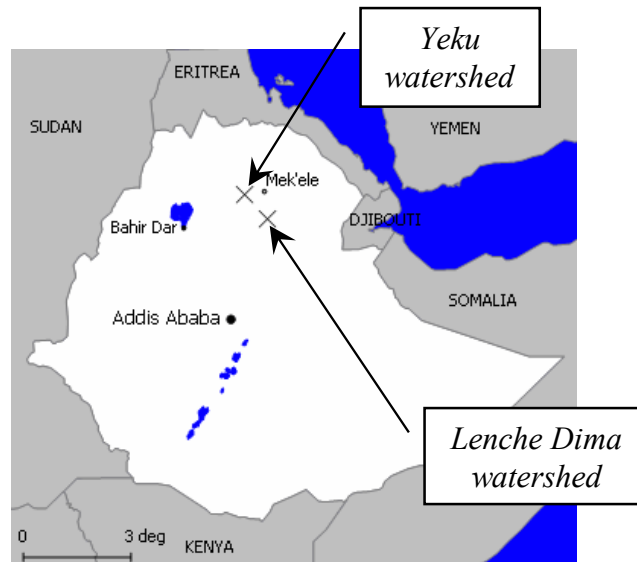


Figure 2.1. Ethiopia site map

Table 2.1. Pilot watershed characteristics

	Altitude (masl)	Yearly Rainfall (mm)	Rain Pattern	Number of House- holds	Average Land- holding Size (ha)	Total Area (ha)	Cultivated Area (ha)
Yeku	2050- 2360	400- 800	unimodal	285	0.75	582	230
Lenche Dima	1520- 1820	700- 1000	bimodal	865	1.56	1546	979

Feasibility studies to select the pilot watersheds were carried out in the late 1990's, with the project officially starting in September 2002. The first community meetings to set watershed priorities were held in January and February of 2003. Leadership



workshops were held then Community Watershed Management Organizations (CWMOs) created in June. With these formal community structures in place conservation projects (both biological and physical) began and continue through the present. Late in each calendar year, project progress is reviewed by the communities and the following year's activities planned. Our involvement with AMAREW stopped at the end of 2005.

### *Watershed Management Design with Limited Data*

When trying a grassroots approach to watershed management, local farmers' knowledge forms the foundation that all other efforts build upon. This approach is especially applicable to places like the pilot watersheds where known information is limited and disparate. Without accurate data, technical experts have no advantage over politicians or stakeholders (Steenhuis and Pfeffer 2000). Yet without these experts, new ideas and management practices will never be introduced. Farmers' knowledge must be supplemented with scientific data collection to properly identify the needs of each watershed.

### *Gathering information*

Obtaining data and making it accessible to both planners and communities is a crucial first step in appropriate watershed development. In the initial watershed selection for the 1999 USAID request for applications, comprehensive feasibility studies were undertaken at the Yeku and Lenche Dima watersheds. A traveling technical team formed a planning group with 30 representative farmers at each watershed then carried out exercises on describing the watersheds, identifying problems, formulating solutions, and developing community action plans for each subsystem of the watershed (Gizaw et al. 1999a and Gizaw et al. 1999b). With assistance the farmers also mapped available

resources, land use, and soils of their watersheds. These in turn were used by the technical team to create scientific maps of the same watershed characteristics. Results from the planning group were presented to the communities, local governments, and cooperating agencies.

Unfortunately, after such a promising start it took four years to begin the actual work. During this break the communities were not kept informed and lost confidence in the project. Other lapses in communication during this time led to important parts of the feasibility study, such as soil maps, being lost. Cases like this underlined the recurring problems associated with participating agencies and groups not sharing the same vision. In a system accustomed to directives coming from above, grassroots initiatives require a daunting amount of inter-agency communication to have a chance at succeeding.

Due to difficult site access, satellite imagery with GPS registration was used to create detailed land use and elevation maps (Heatwole 2003). These maps are very useful for presenting information to technical colleagues, but the technology has not been successfully made accessible to the stakeholders. Further work needs to be done to let all participating parties benefit from this expensive knowledge. While remote sensing may one day provide the basic information needed for watershed management planning in remote locations, the lack of detailed data available for Africa and extreme rainfall patterns mean that onsite data collection is the only real option for now.

The climate data used in the feasibility studies was from the nearest government weather stations, but Ethiopia's highland climate varies greatly both in space and time. Collaborating with the AMAREW project, the government research institution ARARI and graduate students stationed at each pilot watershed researched the effectiveness of

interventions and collected basic scientific data such as rainfall, stream flow, temperature, and evaporation. Enlisting local children allowed for the gathering of a more accurate spatial distribution of data and helped to ensure long-term interest in data collection. Continual monitoring will be essential to successfully adapting management strategies to rapidly changing conditions.

### **Watershed Management through Leadership Development**

Even if all the outputs from initial efforts had been flawlessly preserved, there still was not sufficient information for a top-down watershed development approach that relied on precise hard data for planning. The only practical way to continue was to make full use of community knowledge. To do this the communities needed to be cooperative, informed, and organized such that data and feedback could be relayed with ease. Since time was limited a two-pronged approach was followed: community problems were identified and prioritized in workshops and, at the same time, the community was helped to develop leadership confidence.

#### *Workshops*

Once the project started, community problem identification and prioritization workshops were again held in each watershed. Yeku determined that soil erosion and water shortage were their most important priorities, while Lenche Dima was most concerned with water shortage and crop productivity. Given less priority were fodder shortage, pests, livestock health, deforestation, erratic rainfall patterns, and lack of access roads. The communities then proposed solutions for each problem and, based on their farming timetables, determined how much time could be spent each month on project tasks. These estimates were combined with field visits by technical staff to formulate annual work plans and budget requirements.

### *Organizing communities*

Farming communities have a high interest in improving and protecting their natural resource base but do not always have the capacity to effectively address these issues. Developing leadership skills is essential to these communities wishing to assume more responsibilities. As an initial step various leaders from each community were enrolled in the Community Organizing and Leadership Training for Action (COLTA) program. Upon returning, these leaders were able to hold elections and form the community watershed management organizations (CWMOs). Further trainings were conducted in conflict management, consensus building and community organization. Without such incremental steps, the watershed management organizations would not have been able to organize themselves, coordinate food aid programs, or plan watershed interventions.

Any person receiving food aid automatically became a member of the CWMO in their respective watershed, but each of the four village clusters selected four males and four females to form the organization's leadership. Gender equity was a major concern in strengthening the community participation process. Social and cultural norms combined with a lack of land ownership discourage women from participating in leadership positions. After some initial opposition it has become acknowledged that the 50% rule resulted in a stronger organization. This planning group split into four focus committees: natural resources, crop production, livestock and social development. Greatly enhancing extension possibilities, the influential watershed management organizations also serves as a conduit for further information dissemination such as soil and water conservation, post-harvest storage, and animal health.

### *Promoting Confidence*

The project also targeted households with small or no landholdings for income generation through more informal self-help groups. An example of the success achieved through these programs is the Yeku women's energy group. Increasing scarcity of fuel sources and the necessity of alternative sources of income brought these women together to produce and market improved wood stoves, which reduce fuel use and curb smoke pollution. They currently produce the stoves in the watershed and sell them throughout the Sekota area with the continued support of the Sekota Agricultural and Rural Development Office. Involving women in new income generating activities and leadership opportunities are important emerging components of integrated watershed management projects.

It must be noted that while stakeholder feedback is central to the participatory method, new processes still require the support of outside institutions to seem credible and attainable. Comparing the early progress of the two pilot watersheds made this apparent. The Bureau of Agriculture (BoARD) was the primary partner agency responsible for implementation of the AMAREW project, acting as the interchange point between the communities and outside agencies. BoARD is understaffed and stretched thin, yet at Yeku the supportive representative played a critical role in helping the watershed produce real gains from project works within months. At Lenche Dima, at least three different Development Agents were assigned to the area during the first two years of the project, and sometimes there were months when no one was responsible. Despite the community's interest, very little was accomplished. They needed outside support to help jumpstart the process and build confidence in sustainable development practices.

### **Specific Achievements**

There are encouraging attitudinal changes within the community. In the last three years, through the facilitating role of the CWMOs and the incremental successes of small individual achievements, the communities now contribute 30-40% free labor for watershed management tasks. Maintenance of soil and water conservation structures, tree planting, and access road construction works are carried out through free community labor. This was not the case prior to the AMAREW project, and is a welcome change from the much lamented dependency trap that food aid is often associated with. Increased community responsibility was accomplished by promoting from the start that communities should own the watershed and its activities, whereas outside projects contribute the financial, technical and legal support necessary to create an enabling environment and encourage local initiative.

The vital monitoring of the pilot watershed development is also primarily the responsibility of the CWMO. Each year's activities are evaluated by the communities prior to the next work plan preparation. Farmers identify technologies that have performed well and should be scaled up along with those that should be dropped because of poor performance. Increased confidence and responsibility within the communities has the added benefit of strengthening partnerships between government institutions and the CWMOs.

To illustrate what can be achieved through community participation, specific examples are given on water shortages, land degradation, improved agricultural production and gully rehabilitation.

### *Potable water shortages*

Communities in Yeku identified water shortage as their primary constraint and their first priority for an integrated watershed development effort in their watershed.

Households in the watershed are forced to access on average more than three different water sources during the course of the year to fulfill their domestic and livestock water needs. Water sources include gully sand bed holes, community earthen ponds, rivers, springs and hand-dug shallow wells. Each source has its own constraints: poor water quality and health problems are associated with the ponds and gully beds, springs are especially susceptible to fluctuations in rainfall, and wells can be prohibitively expensive to construct. Most of these sources dry up during the dry periods, so long distances have to be traversed in search of reliable water.

It is women and children of school age, particularly girls, who collect drinking water while boys are responsible for watering livestock by collecting leech-free water from distant rivers. Water scarcity here has significantly impacted enrollment of school-aged children. One farmer explained the situation as follows: “Since the opening of elementary school at Woleh (five kilometers away), the incidence of leeches on our cattle has increased as we started sending our children to school and our livestock are left unattended. I know sending children to school is a good thing but I should give priority to my livestock as they are the ones on which my family’s livelihood depend. That is why I made my children drop out of school and tend the livestock to protect them from getting leeches.”

In line with their prioritization exercises, the community at Yeku developed potential water sources including springs and shallow hand dug wells with support from AMAREW. Labor and locally available construction materials such as sand, stone,

gravel and water were provided by the community while the project provided materials that were not locally available, including cement, reinforcing iron rods, pipes, fittings, and skilled labor. The major new source is the *Bambaw* spring, comprising a spring box with sand filtering system, separate water delivery point for humans and livestock along with a protected washing stand. This spring provides clean potable water for over 200 households and meets the water needs of more than 600 livestock per day. Water use is managed and operated by a water committee established by the community, with moderate usage fees collected to cover routine maintenance and security costs. The newly developed spring has reduced workload for women and children and improved human and livestock health. The farmer quoted above commented the following: “Now that I have access to filtered water from a spring which is leech free, time has come for me to send my children back to school.”

#### *Land degradation*

In addition to water shortage, land degradation and yield reduction were some of the primary concerns of the pilot watersheds. Extensive physical and biological conservation works were carried out in Yeku and Lenche Dima through Food for Work and free community labor mobilization. Physical interventions included extensive hillside terracing, check dams using stone/gabion/sand bags, stone and soil bunds, eyebrow and micro-basins, trenches, sediment storage dams, and rock-fill dams. Biological interventions mainly focused on area closure, gully rehabilitation, hillside planting, and individual homestead plantations. Stabilization of farmland soil by direct sowing on bunds of forage species such as *Sesbania*, *Leucenea*, and pigeon pea has shown very encouraging results. Increased forage production by beneficiaries allowed households to meet livestock feed requirements and enabled some to earn additional money from the sale of forage seeds to the local Bureau of Agriculture (BoARD) and



NGO offices.

The closed area management system in Yeku is one of the finest examples of the cooperative process. Closing off grazing lands when livestock herds were already underfed seemed like a preposterous solution to the communities, so the project arranged for farmers, other community leaders, and local development agents to visit another watershed where closed area management was practiced. After discussing with the more experienced community the difficulties and benefits associated with closed areas, Yeku decided to try closing 25 hectares of their land. Management of these hillside areas was given to self-help groups comprised of persons with limited or no land holdings, often youths or women-headed households. The hillsides showed very rapid regeneration of natural vegetation, resulting in cut and carry profits for the user groups, decreased soil loss, and increased water infiltration and groundwater recharge. This led to seasonal stream flows at Yeku being extended. Due to the success of the trial, the Yeku community has voluntarily closed other grazing areas and become a showpiece watershed that holds Farmers' Days to educate others about closed area management.

#### *Agricultural productivity*

To increase crop yields, experimental farms were established within farmers' plots to test improved varieties of traditional crops and new crops such as cotton, groundnut, and garlic. Some crops, such as beets, grew well but it was quickly discovered that they did not have any market potential in the communities. This kind of instant feedback is not possible at farm trials in specialized outside research sites. Improved plowing techniques aimed at increased water infiltration and storage were also tested in a similar fashion. Subsistence farmers not sure of meeting their required needs are

unwilling to try new methods that could leave them with less food, so aid incentives were used to decrease the risk of technology transfers such as seed storage improvement, fruit tree propagation, private nurseries, beekeeping, and poultry production. Working with local knowledge to select the best locations, small-scale water harvesting structures have also been constructed to enable organic vegetable gardens. Progressive farmers such as Ato Wossen in Yeku now produce a variety of vegetables and fruits such as garlic, pepper, onion, pumpkin, coffee, papaya, avocado and mango using this water. Last year, he was able to get 400 birr (US\$47) from the sale of his garlic crop alone, so other farmers are becoming greatly interested in such improvements.

#### *Gully rehabilitation*

Deforestation exacerbates excess run-off and has caused severe gully erosion in productive farmlands at the foot of hillsides of both pilot watersheds. Increasing amounts of productive farmland are lost through gully erosion every year. While gullies are not the only places in the landscape where erosion takes place, they were the logical candidate to address first since flow is concentrated in relatively small areas, meaning less labor to construct and maintain conservation structures. Another important point is that before the project gullies had no value other than transportation pathways – constructing structures in other areas would almost certainly involve a reduction in the amount of crop or grazing lands.

Therefore, in 2004, a gully in the Kolo Kobo sub-catchment of Lenche Dima was selected for a demonstration of rehabilitation measures. Community level discussions were held on how to rehabilitate gully areas within farm plots, assessing traditional practices and new ideas. It was decided to use simple sand bag check dams since the

stones for gabion construction were scarce. Sand bag check dams are not permanent structures but help trap silt washed from surrounding hillsides. Once adequate silt is accumulated, usually after the first three or four rains, forage species were directly sown on the silt layer. Figure 2.2 shows the significant stabilization that occurred due to these physical and biological interventions.

The CWMO divided the entire gully length into small sections, usually the area between two sand bag check dams, and allocated it to a farmer who had landholdings adjacent to the gully. The user has the right to utilize the vegetation, employing the cut and carry system, in return for maintaining the physical structures before and after the rains and planting trees and other plants as appropriate. During the initial stage of construction, frequent looting of bags, eucalyptus poles, and stone was common. It was not possible to assign guards along the 600 m of gully length, and knowing that government decrees would have little effect, the CWMO turned to *Shelegas*, religious leaders in this Muslim area who use their authority to resolve disputes in the community. The project invited the *Shelegas* to visit the development efforts under way, then a traditional chat chewing ceremony was arranged and the issue of damages to the physical conservation works was brought to the attention of the *Shelegas*. The *Shelegas* uttered a warning statement locally recognized as *Ergeman* stating that “whoever inflicts any damage on the community’s or project’s structures or materials and supplies, may invite Allah’s severe punishment on him.” Since the warning, there has not been any damage reported or materials stolen.



(a) July 2004



(b) October 2004



(c) July 2004



(d) October 2004

Figure 2.2. Kolo Kobo gully rehabilitation photos. Sandbag check dams constructed in main gullies of Kolo Kobo catchment: (a,c) shortly after installation of check dams and (b,d) three months later showing good vegetation cover and gully stabilization.

Gully rehabilitation has been associated with moderating the extremely violent flow events that are associated with intense rainfall patterns, increasing the duration of stream flow and lowering peak rates. We investigated if this was true for the Lenche Dima watershed. Due to the relatively short duration of the study and remoteness of the location, examples are only illustrative. The stream flow patterns in the Kolo Kobo sub-catchment were compared with a control sub-catchment lacking gully stabilization improvements. Although these two micro-catchments within the Lenche Dima watershed were not identical, the results still showed the benefits of interventions. The control sub-catchment, Hartibo, was almost twice as large but had 120 m less of an elevation change as the Kolo Kobo sub-catchment, so standard logic would predict that it have smaller peak discharges and longer retention times. Two runoff events are plotted in Figure 2.3, the first runoff event of the season (a,b) and an event during the middle of the rainy season (c,d). Both storms show the Kolo Kobo gully flow lasting 2-3 times longer than Hartibo, and the first storm (a) shows Hartibo having a much higher peak flow rate. The increased retention time at Kolo Kobo was due to the sandbag check dams holding back water and silt. The many peaks during the 8/14/04 event (b), most notably the last one seen at 5 hours, were likely due to one or more of the check dams being overtopped or giving way, but even with such failures the constructed works did a remarkable job of slowing down erosion. The retention of sediment and moisture in the gully bed can also clearly be seen in Figure 2.2 (a,c). Most years see less than 10 runoff producing storms so it is worth the effort to repair the check dams or construct new ones as the bed fills with soil after each large event.

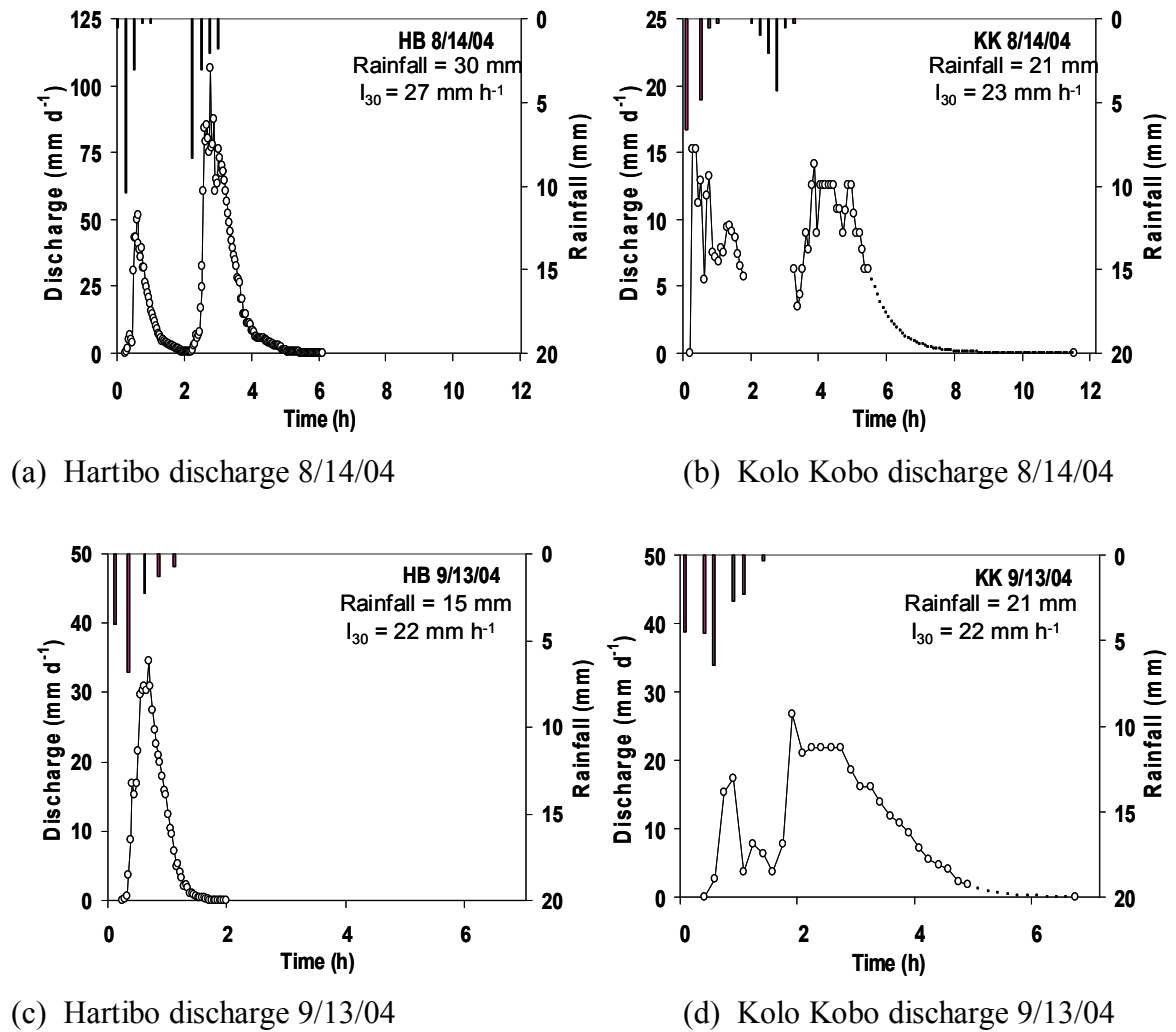


Figure 2.3. Stream discharge and 15-minute rainfall (bar graph) for two sub-catchments in Lenche Dima: “control” Hartibo (HB) and “conserved” Kolo Kobo (KK). Measured values shown by a solid line with open circles and recession fits shown by a broken line.

## Discussion and Conclusions

Bottom-up participatory watershed development process can only be achieved with strong community watershed management organizations (CWMOs), which facilitate the introduction of appropriate management strategies and, even more importantly, continue this effort after outside help leaves. Therefore, our single most important result is that the community organizations have become strong enough to manage

watershed development themselves. Lack of information at the beginning was transformed into a strength by allowing the project to include farmers at a very early point. Involvement in each phase of planning has resulted in increased trust and confidence. This has in turn allowed introduced technologies such as area closures and water harvesting basins to be more readily accepted, and such changes have become desirable with or without outside funding. Empowerment of local organizations allows them to take control of their own watershed problems and work towards meeting their own livelihood needs.

Specifically we have learned that 1) communities have high interest in development initiatives, including sustaining natural resources; 2) only when people make real contributions of their own resources will they strive to ensure the implementation of the planned activities; 3) emphasis must be given to effective organization of communities rather than only focusing on technology development; 4) including non-technical leaders in the information loop provides great benefits at the community level.

Introduced ideas, such as the fair representation of women and poor in the management process, women's micro-enterprise groups, and closing off areas to livestock, faced strong cultural opposition at the beginning but have proven very successful thanks to trial tests and continued collaboration efforts by farmers, non-technical leaders, and project personnel. We also found that communities most at risk were also the most open to new ideas. Lenche Dima was close to a relatively well-off town that offered alternative opportunities for income, so the establishment of a committed CWMO in Lenche Dima was initially difficult. Only after a project manager stayed for a two-month period in the watershed demonstrating what could be achieved by cooperation did the CWMO take off. In contrast, farming was the sole option for people in the



more remote Yeku watershed, so it was easy for them to see the importance of improving their natural resource base. Motivation was thus much stronger in Yeku, and their CWMO immediately started making progress. A good measure of the strength of this community organization is that three years after its inception approximately 40% of the conservation works labor was being implemented through volunteer work instead of foreign aid. We have not yet been back to Lenche Dima.

Without ignoring the encouraging improvements described above, many challenges still exist for these pilot watersheds. In a society that is used to top-down administration, having a strong community base is not by itself enough. Since the government currently owns all land, communities and individuals will not be able to take full responsibility for their natural resources until further reform of land rights is pursued. In addition, stakeholder scientists and engineers are still required to draw upon their wider ranges of experience to ensure the sound design, solid construction, proper use and implementation, and appropriate maintenance of new technologies. The project involves numerous government agencies and foreign universities, but all the partners do not have the same vision. Gains will quickly falter unless the project continues to build organizational relationships and recognize changing needs.

Luckily, even localized successes, such as the progress seen in the pilot watersheds, work like a positive feedback loop, leaving those involved more capable of tackling larger problems. Examples discussed from both watersheds have illustrated the effectiveness and influence of small-scale projects. Projects at the local level are less likely to overwhelm the resources of an organization or exclude them, and both the local communities and stakeholder organizations that work together in these projects improve their decision-making powers and sense of ownership. The pilot watersheds



of Yeku and Lenche Dima have become showpieces for watershed conservation, motivating and teaching other communities that similar progress is within their reach.

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## CHAPTER 3

### Simple Rainfall-Discharge Relationships for Ethiopian Watersheds

#### **Introduction**

The amount and quality of hydrologic data collected in Africa are rapidly growing, with the appropriate organization and analysis of these data becoming especially important towards gaining real benefits from many projects. Engineering solutions such as the Rational Method have been utilized (Desta 2003), but even in locations without advanced technical resources, there is often the tendency to apply complex, established models such as the Precipitation Runoff Modeling System (PRMS) (Legesse et al. 2003), Water Erosion Prediction Project (WEPP) (Zeleeke 2000) or the agricultural non-point source (AGNPS) pollution model (Mohammed et al. 2004). These models and methods have been developed for temperate climates, and may not apply to the monsoonal climates of Africa. Moreover, all of these models are based on the assumption that runoff is created by infiltration excess processes, where runoff occurs when the precipitation rate exceeds the infiltration capacity of the soil. Infiltration measurements and plot studies in Ethiopia have shown, however, that the infiltration rates, especially on hillsides with stone cover, can be of the same order of magnitude or higher than the greatest rainfall intensity (McHugh 2006). Thus, although infiltration excess can occur, the most likely mechanism that produces the majority of the runoff is saturation excess in which the shallow soil becomes saturated (either from the rainfall or from interflow from upslope areas) and produces runoff. Zeleeke (2000) found that the WEPP model was not responding to changes in  $K_b$ , particularly during peak rainy season, and recommended improving the hydraulic component of his model so that soil saturation had more effect on the calculated peak runoff. Methods that are less

dependent on the type of runoff focus on water balances (e.g. Johnson and Curtis 1994, Conway 1997, Kebede et al. 2006, and Mishra et al. 2006) and may prove to be a more robust and parsimonious solution to the problem.

Knowledge of the basic runoff mechanisms is necessary before an appropriate model formulation can be selected. To derive these mechanisms, we use a water balance method employing existing data in three small watersheds and then use the outcome of these water balance calculations to suggest runoff mechanisms that may explain the observed pattern.

## **Methods**

The Soil Conservation Research Programme (SCRCP) was an extensive project implemented from 1981-1998 to help understand land degradation processes and generate imperial evidences to combat land degradation in Ethiopia. It was administered by the Ethiopian government, primarily the Ministry of Agriculture, and the Center for Development and Environment (CDE) of Bern University. The project was funded by the Swiss Agency for Development and Cooperation (SDC). Through this project seven research sites were established around the country to generate data on land degradation (soil loss, runoff, catchment discharge, etc.) and field test soil conservation methods and collect baseline data. An impressive database of information was built, with the intention of continued data collection after the project ended. This study uses hydrologic data collected from the three research stations in the Amhara National Regional State: Andit Tid, Anjeni, and Maybar (Figure 3.1). All three sites are agricultural lands with extensive soil erosion control structures built to assist the rain-fed subsistence farming, but the watersheds differ in size, topographic relief, and climate (Table 3.1).

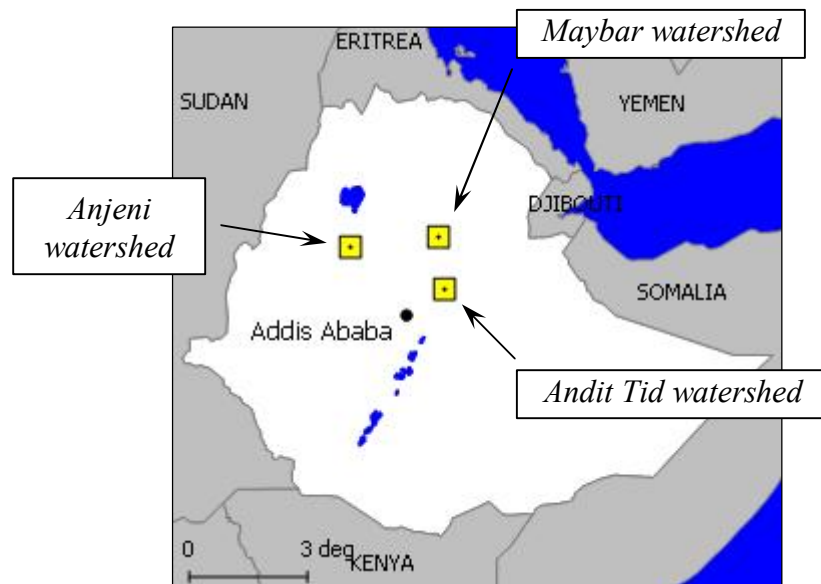


Figure 3.1. Location of the three SCRPs within Ethiopia.

Table 3.1. Overview of the three SCRP watersheds

	<b>Andit Tid</b> <sup>1</sup>	<b>Anjeni</b> <sup>2</sup>	<b>Maybar</b> <sup>3</sup>
Area (ha)	477.3	113.4	112.8
Elevation range (m)	3040-3548	2407-2507	2530-2858
Mean annual temp (°C)	12.6	16	16.4
Mean annual rainfall (mm)	1467	1675	1417
Mean annual evaporation (mm)	1174	1400	1147
Rainfall pattern	Bimodal	unimodal	bimodal
Growing season (days)	175	242	175
Pop density (persons/km <sup>2</sup> )	146	193	188
Primary crops	barley	barley, cereals, beans and oils	cereals, maize
Major soils	Andosols, Fluvisols, Regosols, Lithosols	Alisols, Nitosols, Cambisols	Phaeozems, Lithosols, Gleysols
Years of data available	12	10	11
Long-term <i>Q/P</i> ratio	0.54	0.43	0.32

<sup>1</sup> (SCRP 2000a)<sup>2</sup> (SCRP 2000b)<sup>3</sup> (SCRP 2001)

SCRP trained local research assistants in each respective watershed to collect data continuously. Rainfall was measured with automatic pluviographs and daily evaporation was measured with screened Piche evaporimeters. Daily maximum and minimum temperatures were measured in the air (1.5 m above ground) and the soil surface (0.1 m above ground) along with manual rain gauge readings. Stream flow discharge from each catchment was determined from automatic float gauges combined with manual stage readings. Further information on the initial data collection and processing can be

found in Hurni (1984) and Bosshart (1997).

Many of the daily potential evaporation measurements during the dry months were quite high, sometimes over 10 mm/day. These were affected by the dry landscape surrounding the measurement sites (Brutsaert 2005) and did not seem reasonable for these montane locations; hence minimum and maximum temperatures were used also to calculate Penman-Monteith estimates (Allen et al. 1998) of the potential evapotranspiration ( $ET_0$ ) rates for a reference crop in each of the three watersheds. Maximum calculated  $ET_0$  values for Andit Tid, Anjeni, and Maybar were 5.0 mm/day, 7.6 mm/day, and 6.9 mm/day, respectively. These values corresponded well with a 7 mm/day ceiling that has been widely used, so this theoretical ceiling was applied to all evaporation values before further analysis.

Daily rainfall, evaporation, and discharge data were summed over weekly, biweekly and monthly periods to find the most appropriate representation of watershed behavior. For most analyses, precipitation – evaporation ( $P-E$ ) was used instead of just precipitation, since we found that the combined value was a more accurate estimate of the water available for movement or storage in the soil. In addition, to study the effect of watershed moisture status, cumulative rainfall during each season was calculated. Since the highlands of Ethiopia have wildly fluctuating spatial/temporal rainfall distributions, a simple but consistent method to delineate seasons had to be developed iteratively. Instrumenting the deep Haplic Phaezem soils found in Maybar, Bono and Seiler (1987) found that 9-10 rainless days dried out a wet soil to a depth of 10 cm, and 28-29 days dried out the soil to 50 cm. Thus the following algorithm was developed for delineating seasons: if the number of days with  $P-E > 0$  within the last 30-day period was greater than or equal to 10 and the 30-day sum was positive, then the “rainy season” was



initiated. If there were zero days with  $(P-E) > 0$  within the previous 14-day period then a rainy season was stopped. The “dry season” was defined as the remaining part of the year.

## Results

Temporal dynamics were found to play an important role in the hydrologic behavior of the watersheds. Plots of daily rainfall and runoff values were not particularly well correlated. In conjunction with the short and sometimes intense rainstorms found in this region at the beginning of the rainy season, all three watersheds typically produced runoff immediately after a large storm. However, as shown in Figure 3.2, less intense storms at the end of rainy season could also create more extended periods of runoff. Using daily values gave misleading relationships in these cases.

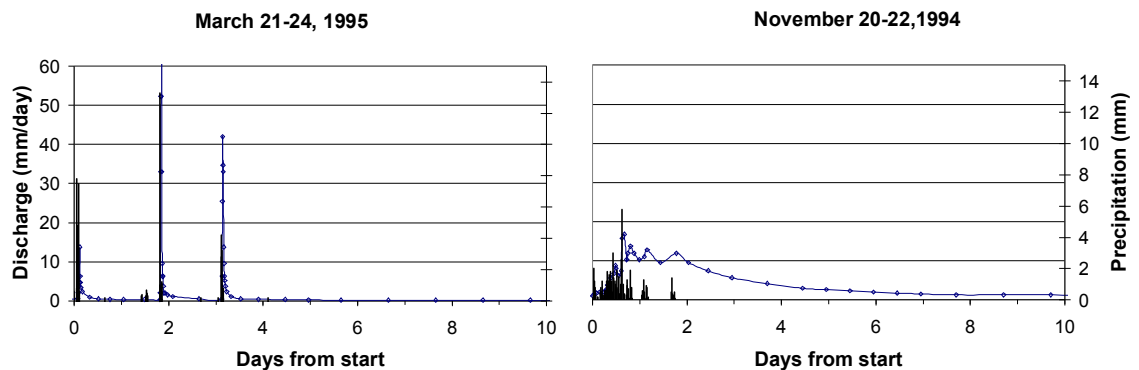
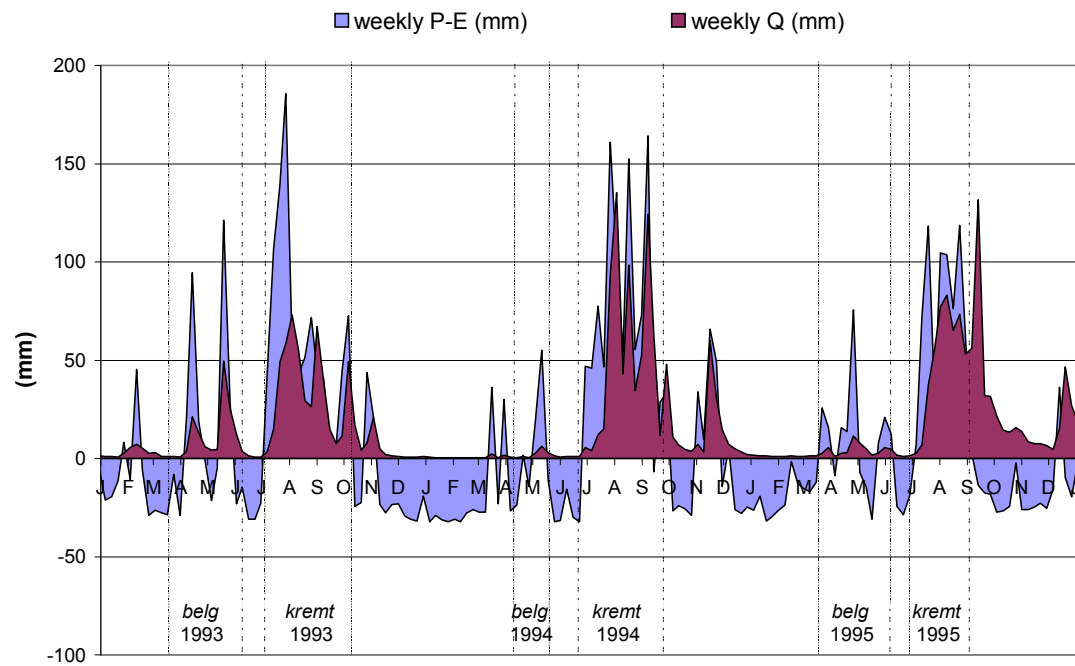


Figure 3.2. Example storm hydrographs for Andit Tid. The March 21-24, 1995 event is at the beginning of the small *belg* rainy season, while the November 20-22, 1994 event is in the dry period that follows the large *kremt* rainy season. Precipitation is shown with bars and discharge with connected circles.

Thus we determined that weekly sums were most suitable for producing overview hydrographs (Figure 3.3) that still retained the influence of peaks from individual storms, but also clearly conveyed when watersheds were in water deficit and when they

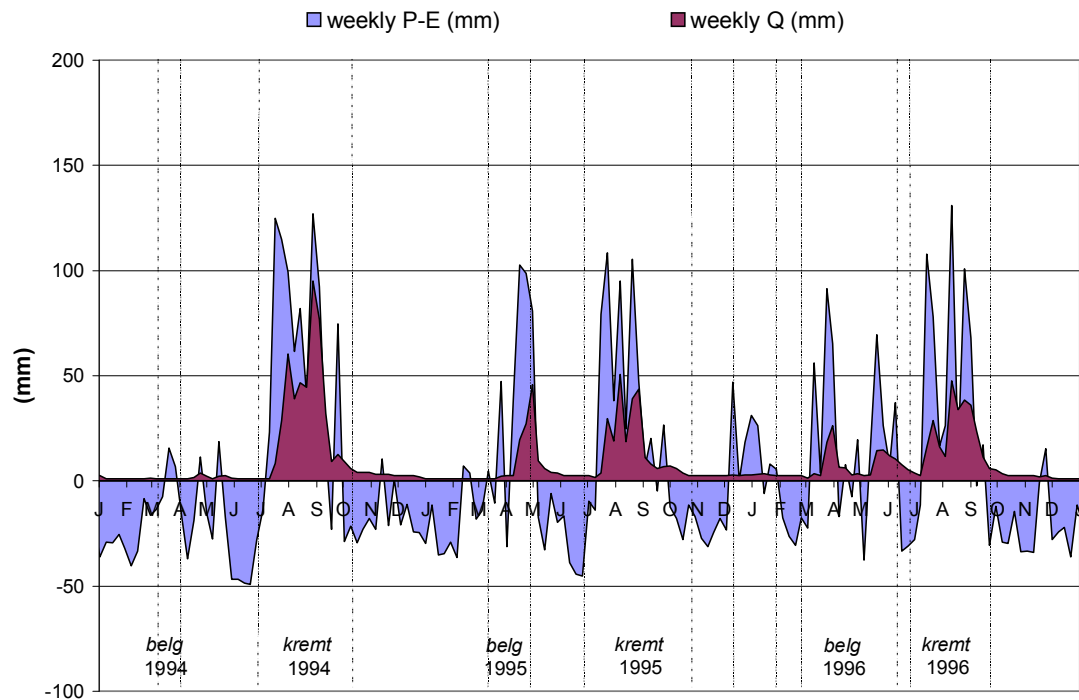
became saturated and subsequently produced rapid runoff responses. When looking for rainfall-discharge relationships, longer time periods were required to capture the stream responses in order to include the interflow component. Both biweekly and monthly summations were able to adequately show the linked responses but biweekly divisions resulted in twice as many points so were selected for comparison analyses.



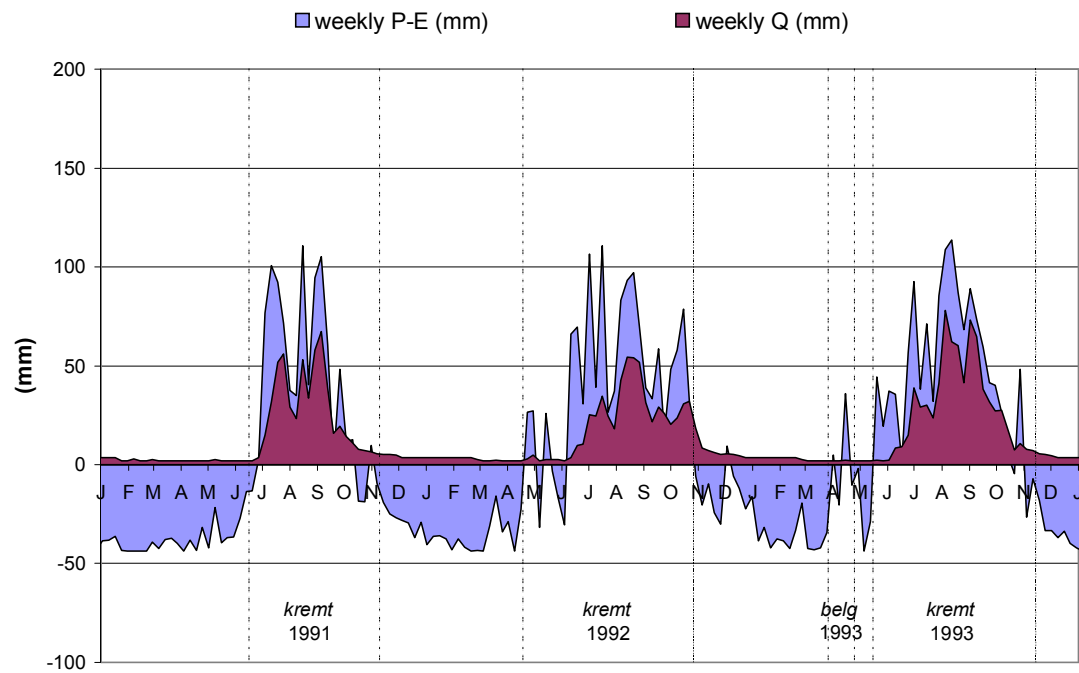
(a) Andit Tid 1993-1995

Figure 3.3. Example overview hydrographs for Andit Tid (a), Anjeni (b), and Maybar (c). Time scale is shown in months but values are weekly sums. Delineation of seasons is shown with vertical dotted lines.

Figure 3.3 (Continued)



(b) Anjeni 1991-1993



(c) Maybar 1994-1996

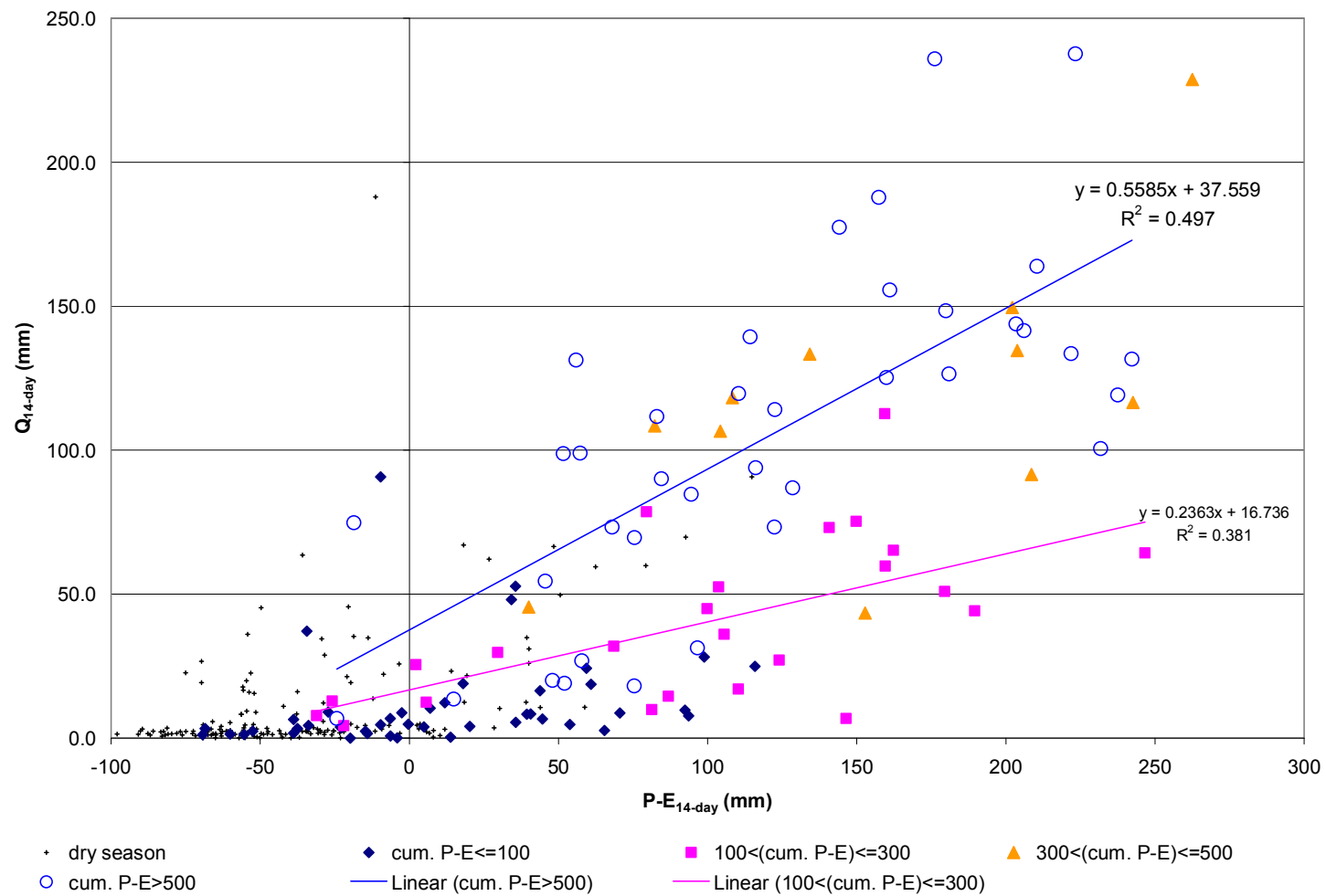
Andit Tid, the largest study site, was also the highest and least populated. Hill slopes were very steep and degraded, resulting in 54% of the long-term precipitation becoming runoff. Despite its larger size, stream flow quickly returned to nearly zero during the typically dry months of November through March. During the larger *kremt* wet season, normally June through October, after a few storms wet the soils, most of the effective rainfall ( $P-E$ ) became runoff (Figure 3.3a). However, stream discharges did not immediately return to dry season levels; instead, they steadily decreased (e.g. October-December 1995 in Figure 3.3a).

Anjeni, located in one of the country's more productive agricultural areas, was the lowest in elevation and highest in population density. This site receives more rain than the other two and has only one rainy season, typically May through October. In similar fashion to Andit Tid, the Anjeni watershed required only a few storms at the beginning of each wet season to satisfy the watershed storage and begin producing runoff (Figure 3.3b). Unlike Andit Tid, where discharge peaks often overlapped the effective precipitation peaks, at Anjeni the discharges were a smaller proportion of the ( $P-E$ ), and only 43% of the long-term rainfall ended up at the watershed outlet (Table 3.1). Some possible explanations for the observed difference could be slope type (which is gentle in Anjeni), soil type (better infiltration capacity and in some cases deep) and most importantly, the Anjeni watershed is well treated by physical soil and water conservation measures.

Finally, Maybar behaved in a similar manner to Anjeni, except for the difference in rainy season patterns (Figure 3.3c). Thirty-four percent of the long-term precipitation in Maybar became discharge at the outlet.

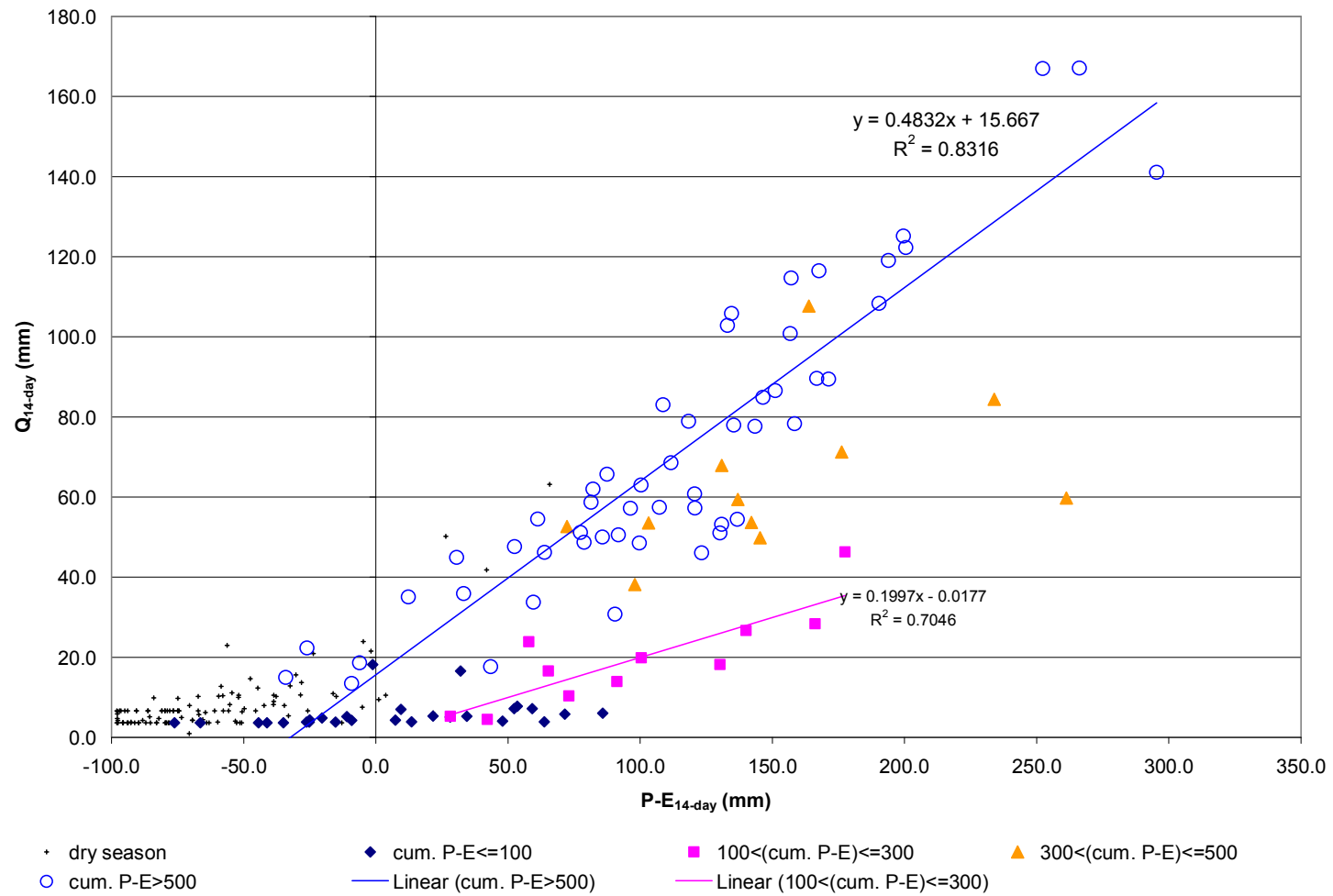
To further investigate runoff response patterns, the biweekly sums of discharge were plotted as a function of effective rainfall (i.e.,  $P-E$  for a two week period) during the rainy season and dry season (as defined earlier) in Figure 3.4. Figure 3.4 shows that the watershed behavior changes as the wet season progresses, with precipitation later in the season generally producing a greater percentage of runoff. As rainfall continues to accumulate during a rainy season, each watershed eventually reaches a threshold point where runoff response can be predicted by a linear relationship with effective precipitation, indicating that the proportion of the rainfall that became runoff was constant during the remainder of the rainy season. For the purpose of this study, an approximate threshold of 500 mm of effective cumulative rainfall,  $P-E$ , was selected after iteratively examining rainfall vs. runoff plots for each watershed. The proportion  $Q/(P-E)$  varies within a relative small range for the three watersheds. In Andit Tid approximately 56% of late season effective rainfall,  $P-E$ , became runoff (Table 3.2), while Anjeni and Maybar were 48% and 50%, respectively. There was no correlation between biweekly rainfall and discharge during the dry seasons at any of the sites.

Figure 3.4. Biweekly summed rainfall/discharge relationships for Andit Tid (a), Anjeni (b), and Maybar (c). Rainy season values are grouped according to the cumulative rainfall that had fallen during a particular season, and a linear regression line is shown for the wettest group in each watershed.



(a) Andit Tid 1987-1998

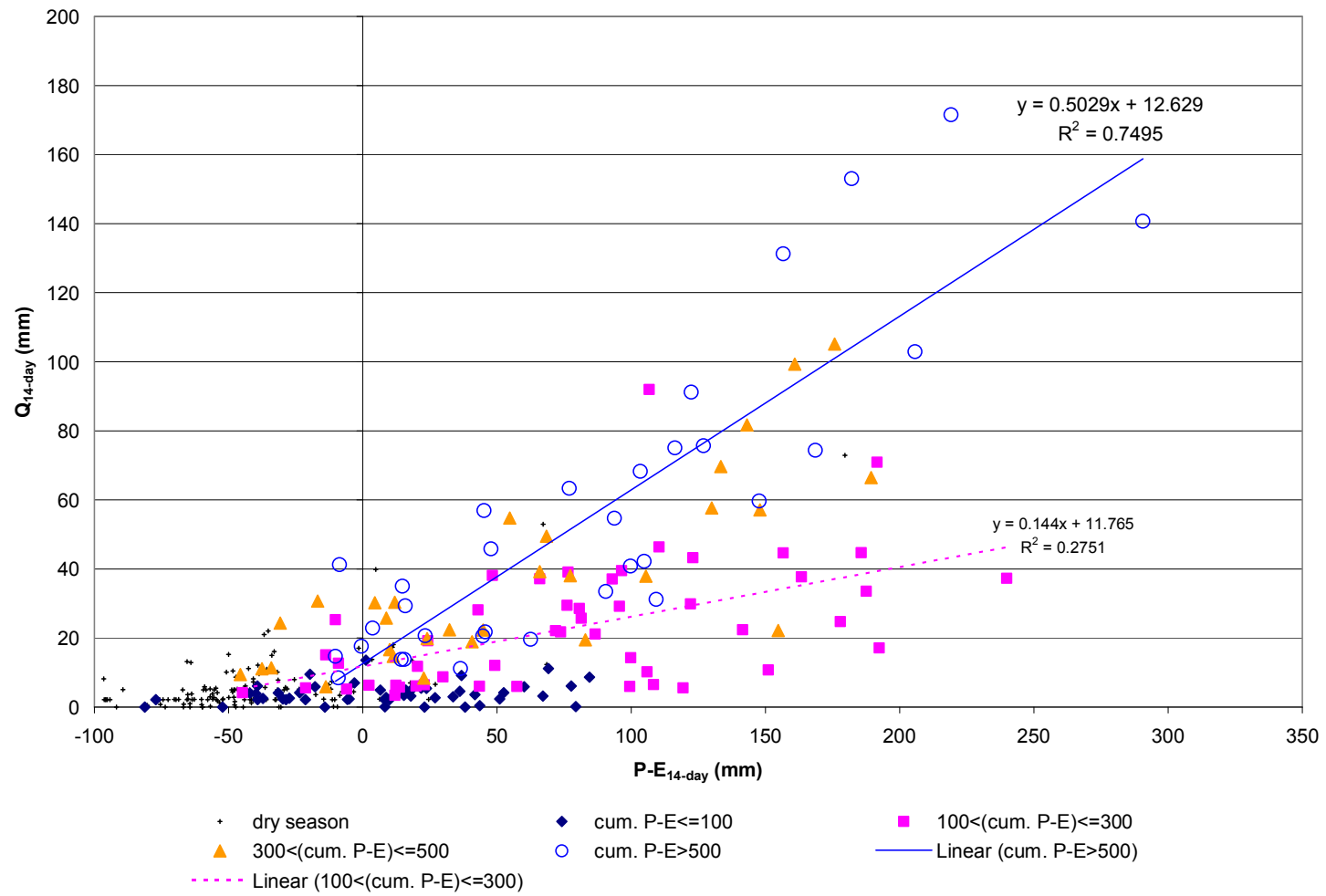
Figure 3.4 (Continued).



(b) Anjeni 1987-1997



Figure 3.4 (Continued).



(c) Maybar 1988-2001

Table 3.2. Summary of linear rainfall-discharge relationships found during latter part of the rainy season.

Watershed	Figure	Cumulative ( <i>P-E</i> ) threshold <sup>1</sup>	Slope	Intercept (mm)	$r^2$
Andit Tid	3.4 (a)	~500 mm	0.56	38	0.50
Anjeni	3.4 (b)	~500 mm	0.48	16	0.83
Maybar	3.4 (c)	~500 mm	0.50	13	0.75
All three combined	3.5	~500 mm	0.56	40	0.61
Anjeni & Maybar together	3.5	~500 mm	0.49	14	0.80

<sup>1</sup>The amount of cumulative rainfall in a season after which the watershed responds in a consistent fashion

<sup>2</sup> Relationships here are for biweekly summations of (*P-E*) and *Q*

Since each of the study sites showed a similar linear response after the threshold cumulative rain was satisfied, the latter parts of the wet seasons were all plotted in the same graph (Figure 3.5). Despite the great distances between the watersheds and the different characteristics, the response was remarkably similar. The Anjeni and Maybar watersheds had almost the same runoff characteristics, while Andit Tid had more variation in the runoff amounts but on average the same linear response with a higher intercept (Figure 3.5). Linear regressions were generated for the combined results of all three watersheds, and for the Anjeni and Maybar watersheds grouped together, with the combined watershed regression having less correlation ( $R^2 = 0.61$  compared with 0.80). The regression slope does not change significantly, but this is due to the more similar Anjeni and Maybar values dominating the fit (Table 3.2). Note that these regressions are only valid for the end of rainy seasons when the watersheds are wet.

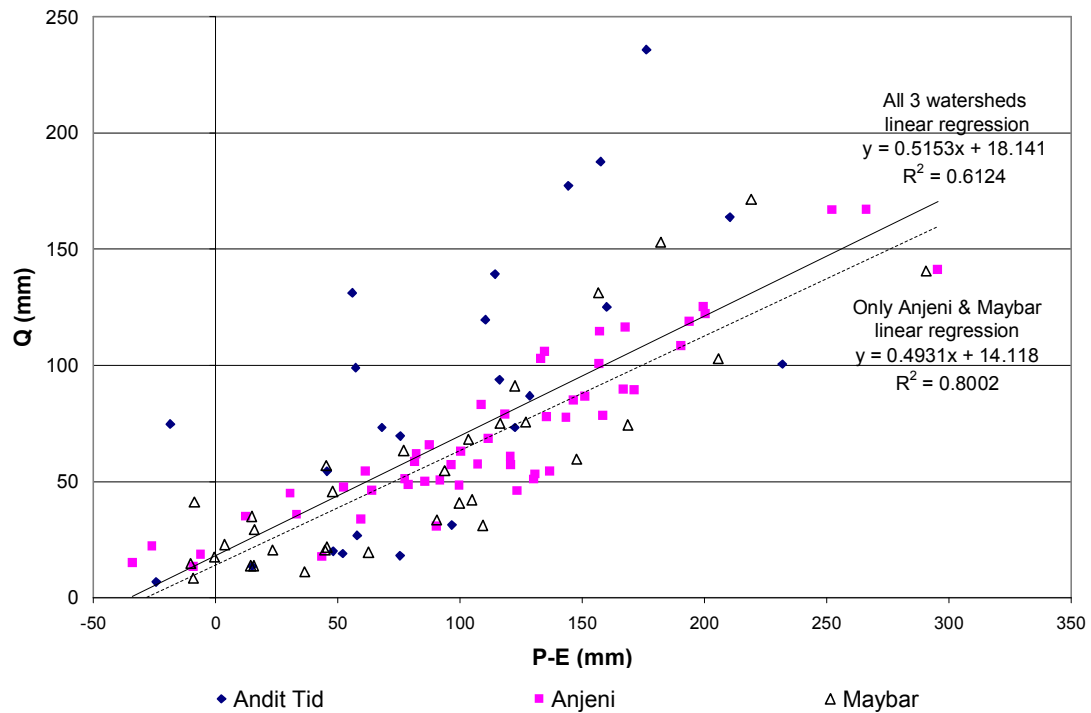


Figure 3.5. Biweekly summed rainfall/discharge relationships for all three watersheds but only during the latter part of the rainy seasons, after 500 mm of cumulative rainfall ( $P-E$ ) has fallen. Linear regressions are provided for the combined plots: all three together are shown with a solid line and only Anjeni and Maybar (together) are shown with a dotted line.

## Discussion

Why these watersheds behave so similarly after the threshold rainfall has fallen is an interesting question to explore. It is imperative, therefore, to look at various time scales, since focusing on just one type of visual analysis can lead to erroneous conclusions. For example, looking only at storm hydrographs of the rapid runoff responses prevalent in the typically intense Ethiopian storms, one could conclude that infiltration excess is the primary runoff generating mechanism. However, looking at longer time scales in Figures 3.3 and 3.4, it can be seen that the ratio of  $Q/(P-E)$  is increasing with cumulative precipitation. Consequently, the watersheds behave differently depending on how much moisture is stored in the watershed, suggesting that

saturation excess processes play an important role in watershed response. If infiltration excess was controlling runoff responses, discharge would only depend on the rate of rainfall, and there would be no clear relationship with antecedent precipitation as is clearly the case looking at Figures 3.3 and 3.4. The finding that saturation excess is occurring in watersheds with a monsoonal climate is not unique. For example, Hu et al. (2005), Lange et al. (2003), and Merz et al. (2006) found that saturation excess could describe the flow in a monsoonal climate in China, Spain, and Nepal respectively. There are no previous observations published for Ethiopia on the suitability of these saturation excess models to predict runoff, except that of Zeleke's (2000) observations and recommendations, but attempts to fit regular models based on infiltration excess principles result in extremely poor fits (Haregeweyn and Yohannes 2003). This does not mean that there is no infiltration excess overland flow at all, and both could occur during particularly high intensity storms. However, as shown by van de Giesen et al. (2000) in the Ivory Coast a large portion of the overland flow re-infiltrated after the rain stopped before reaching the channel.

Results from this study should be validated on other sites as data become available, but perhaps the following generalizations could be used as a first estimate when discharge measurements are not available for similar watersheds in Amhara: for cumulative rainfall up to 100 mm it all infiltrates; for cumulative rainfall from 110 to 300 mm approximately 20% of the watershed area contributes; and for cumulative rainfall above 500 mm approximately 50% of the effective precipitation becomes runoff. Note that most runoff occurs later in the season during an important time of crop growth, so relatively simple analyses like this could be useful in estimating available water and by extension seasonal yields.

Of course, such generalizations must be used cautiously since runoff mechanisms are dependent on a multitude of factors. Andit Tid, being more than four times as large as the other sites, displayed a wider range of runoff responses to individual storm events, depending on the time of year. This size advantage conversely allowed Andit Tid to account for a much greater percentage of rainfall since a larger fraction of water likely circumvents the stream gauge in the smaller watersheds.

### **Conclusions**

Rainfall-runoff relationships in three small watersheds with more than 10 years of record were analyzed. Each of the watersheds has a limited amount of storage, with certain confluence areas quickly becoming saturated and directly contributing runoff with additional rainfall. Eventually, as the rainy season continues, any areas of the landscape that have the potential to contribute runoff become wet enough that this fixed percentage of each watershed produces rapid flow in any later events. For the three watersheds in this study, the point at which potential runoff sites consistently become active occurs after approximately 500 mm of cumulative effective rainfall has fallen and represents nearly 50% of the watershed area.

Water balance methods such as the one presented in this study are relatively easy to perform, yet can produce needed insight into the water transport process that occurs in the remote highlands of Ethiopia. It is of interest to apply this method to other monsoonal climates to understand if our observations apply to other areas in the world as well.

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## CHAPTER 5

### Conclusions

Ethiopian watershed managers must deal with a diverse range of situations. No watershed is exactly alike, and the amount and quality of information regarding each site varies wildly. Two common levels of available information in Ethiopia have been presented, with different analysis methods being chosen for each situation. A participatory descriptive method was selected for Yeku and Lenche Dima and an analytic descriptive method for Andit Tid, Anjeni, and Maybar.

Chapter 2 examined a situation where very little scientific information was available for watershed development. Additionally, since there is such a diverse collection of stakeholder groups involved with the Yeku and Lenche Dima pilot watersheds, analyses must be performed and results presented in a way that is accessible by the entire range of the intended audience. For instance, a detailed analysis of how stochastically randomized porosity values could lead to more realistic moisture patterns when modeling their watershed would not be useful information to most of the stakeholders in this situation. Instead, utilizing a participatory development method makes subsequent information dispersal much easier since the planning already includes a range of viewpoints. Investments made upgrading the leadership capacity of local communities pay great dividends when outsiders visit the watersheds – farmers can confidently explain how and why they prioritized activities, donated volunteer labor towards the conservation works, and adopted new practices such as closed area management. This confidence allows the local communities to continue to actively seek out better ways of protecting their natural resources, possibly leading to more complex studies such as the one discussed in Chapter 3.



Continued improvements to the research infrastructure will lead to even more successes. Those involved in watershed development should give particular attention to disseminating project outputs, such as soil surveys and high resolution aerial maps, to as many involved persons as possible, especially those that actually live in the study areas. The availability and consistent organization of the raw SCRP information used in Chapter 3 has been instrumental to producing a prodigious number of papers and reports that have helped improve soil conservation practices in Ethiopia. Such openness of information can only lead to greater understanding of the underlying hydrologic processes in these watersheds.

Chapter 3 looked at a situation where technical information was available, but the best use of this data was uncertain. To most effectively prove that this hydrologic data has valuable uses, analyses of the watersheds should be targeted at natural resource managers within the regional government agencies that now control the research sites. Developing simple rainfall-discharge relationships was presented as one such analysis. Insights gained, such as the predictable late rainy season behavior and importance of runoff mechanisms besides infiltration excess could be used as a guide towards starting other research paths. Some possible topics would be topographic index relationships, water balance models, and special investigation into the hydrologic effect of soil conservation structures. These kinds of studies would further demonstrate the benefit of maintaining the research infrastructure that has been established in Andit Tid, Anjeni, and Maybar.

In summary, this thesis confirms that each hydrologic analysis has its own merits, but taken out of the proper context any specific method could prove useless. The level of

information available and intended audience must always be carefully considered when successfully investigating a watershed.